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Mass hierarchy and localization of gravity in extra time *

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Abstract: We consider Randall-Sundrum model with localized gravity, replacing the extra compact space-like dimension by a time-like one. In this way the solution to the hierarchy problem can be reconciled with a correct cosmological expansion of the visible universe, just as a trivial result of the sign flip of cosmological constants in the bulk and on the 3-branes relative to the case of extra space-like dimension. Some phenomenological aspects of the proposed scenario related to the tachyonic nature of Kaluza-Klein states of graviton are also discussed.

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During the few past years it has been realized that the fundamental scales of physics can be altered in the presence of extra dimensions [1, 2, 3]. What is exceptionally exciting is that the fundamental Planck scale [2] or/and fundamental GUT scale [3] can be lowered to potentially accessible energies in the multi-TeV range. In addition to the well known explanations within the supersymetric models or the models with dynamical symmetry breaking, these observations offer a qualitatively new explanation of the observed hierarchy between the electroweak scale and high energy scales. Despite the important differences between these two scenarios, both similarly utilize δ extra compact dimensions with large compactification radii r_n $(n = 1, ..., \delta)$ in the factorizable, $M^4 \times N^\delta$, $(4 + \delta)$-dimensional spacetime and thus the apparent weakness of gravity in the visible four-dimensional world (M^4) is explained due to the large volume V_{N^δ} of the extra-dimensional submanifold N^δ (for an earlier proposal of large extra dimensions, see [4])[1]:

$$M_{Pl}^2 = M_*^{\delta+2} V_{N^\delta}, \tag{1}$$

where M_* is the fundamental high-dimensional scale and M_{Pl} is the ordinary four-dimensional Planck scale.

More recently, a new scenario [7] for generating Planck/weak scale hierarchy has been proposed within the framework of 5-dimensional non-factorizable AdS_5 space-time with two 3-branes located at the S^1/Z_2 orbifold fixed points of the fifth compact dimension. Now the weakness of gravity in the visible world 3-brane is explained without recourse to large extra dimensions, but rather as a result of gravity localization on the hidden 3-brane. Gravity localization in such scenario occurs because the five-dimensional Einstein's equations admit the solution for the space-time metric with a scale factor (”warp factor”) which is a falling exponential function of the distance along the extra dimension y perpendicular to the branes[2]:

$$ds^2 = e^{-2k|y|} dx_{1+3}^2 + dy^2, \tag{2}$$

when the bulk cosmological constant Λ $(\Lambda < 0)$ and the tensions T_{vis} and T_{hid} of the

[1]It has been recently proposed [5] that the vacuum expectation value of the electroweak Higgs boson can be exponentially suppressed due to the renormalization effects in higher dimensional theories, thus explaining Planck/weak scale hierarchy without need of hierarchically large extra dimensions. For another approach to solve the hierarchy problem within the higher dimensional gauge theories see [6].

[2]Earlier, it was suggested in [8] that gravitational interaction between particles on a brane in uncompactified five-dimensional space could have a correct four-dimensional Newtonian behaviour, provided that the corresponding contributions to Newton's law from the bulk cosmological constant and from the brane tension cancel each other. For some previous related works, see [9].

visible and hidden branes respectively are related according to[3]:

$$T_{hid} = -T_{vis} = 6M_*^3 k, \quad k = \sqrt{-\frac{\Lambda}{6M_*^3}}. \tag{3}$$

Thus, graviton is essentially localized on the hidden brane with positive tension ($T_{hid} > 0$) which is located at $y = 0$ fixed point of the S^1/Z_2 orbifold, while the Standard Model particles are assumed to be restricted on the visible brane with negative tension ($T_{vis} < 0$) which is located at $y = \pi r_c$ (r_c is the size of extra dimension) orbifold fixed point. So, a hierarchically small scale factor generated for the metric on the visible brane gives an exponential hierarchy between the mass scales of the visible brane and the fundamental mass scale M_*, after one appropriately rescales the fields on the visible brane. In fact, assuming $M_* \sim M_{Pl}$, TeV-sized electroweak scale can be generated on the visible brane by requiring $r_c \cdot M_* \simeq 12$. Various modifications and generalizations as well as interesting phenomenological and cosmological aspects of this scenario are intensively discussed in the literature [9-16].

Soon after Ref. [7] appeared it was pointed out in [10] that having a negative tension visible brane would be problematic from the cosmological point of view, since Friedmann's equation governing the expansion of the visible universe appears with wrong sign. In fact, Einstein's equations posses another solution [8, 11] which can be obtained from (2) by changing the sign of the k parameter:

$$k \to -k. \tag{4}$$

Since the transformation (4) is not a symmetry of the theory (unless simultaneously accompanied by the shift $y \to y + \pi r_c$) the solution with $k < 0$ is physically distinct from the solution with $k > 0$ and, as evident from (3), replacement (4) exchanges the signs of brane tensions, so that the visible brane at $y = \pi r_c$ becomes now the one with positive tension. However, while the solution with $k < 0$ [8, 11] is consistent with a Friedmann-like expanding universe, the generation of Plank/weak scale hierarchy becomes now impossible. To reconcile the cosmological expansion with the solution of the Plank/weak scale hierarchy problem, more complex constructions have been subsequently considered [12, 13][4].

In this letter we would like to suggest that the problems of mass hierarchy and cosmological expansion can be simultaneously solved just in the frame of the original proposal of Ref. [7] by simply replacing the extra space-like dimension by a time-like

[3]Actually this relation is nothing but the condition for the vanishing of the four-dimensional effective cosmological constant.

[4]It was realized later that the solution to the problem of correct cosmological expansion of the visible brane can be linked to the problem of stabilization of extra space [13]. See [14] for the stabilization mechanisms.

one[5]. Our solution arises from a rather simple observation: The replacement of the space-like dimension by a time-like one, $y \to \tau$, i.e. the change of the signature from $(-++++)$ to $(-+++-)$ leaves Einstein's equations unchanged if it is simultaneously accompanied by the change of the sign of bulk cosmological constant Λ and the brane tensions T_{hid} and T_{vis}:

$$\begin{gathered}(-++++) \to (-+++-)\\ \Lambda \to -\Lambda, \quad T_{hid} \to -T_{hid}, \quad T_{vis} \to -T_{vis}.\end{gathered} \tag{5}$$

Thus, in our scenario the AdS$_5$ space is replaced by the dS$_5$ one and the solution for the metric

$$ds^2 = e^{-2k|\tau|}dx^2_{1+3} - d\tau^2 \tag{6}$$

leads to the localization of gravity on the hidden brane with negative tension stuck at the $\tau = 0$ fixed point of the time-like S^1/Z_2 orbifold, while the Standard Model particles are placed on the positive tension brane at $\tau = \pi\tau_c$ with

$$-T_{hid} = T_{vis} = 6M_*^3 k, \quad k = \sqrt{\frac{\Lambda}{6M_*^3}}. \tag{7}$$

The Planck/weak scale hierarchy is explained even with a small (in Planck mass units) period of extra time (such as, $\tau_c \cdot M_{Pl} \approx 12$), in full analogy with the case of space-like extra dimension [7], while the positivity of the visible brane tension ($T_{vis} > 0$) ensures the correct Friedmann-like expansion.

Despite the similarity of solutions with extra space-like (2) and extra time-like dimension (6), the phenomenological consequences of these two scenarios drastically differ. As it is well known, typically theories with extra time-like dimensions suffer from pathologies such as negative-norm states (ghosts) and tachyons[6]. In fact the Kaluza-Klein (KK) excitations in the case of compact extra time-like dimensions would be seen by the four-dimensional observer as tachyonic states with imaginary masses quantized in units of $\frac{i}{\tau_c}$. The exchange of such KK states induces an imaginary part in the effective low-energy potential between two test "charges". This complexity was interpreted in [24] as a violation of causality and probability in the interaction of two "charged" particles, so they can disappear into "nothing". If so, from the experiments dedicated to look for proton or double β decays one can put rather severe bounds on the size of extra time-like dimension, $\tau_c \lesssim 10 \cdot M_{Pl}^{-1}$ [24], in the case of appearance of tachyonic KK states of photon or gluons. Recently,

[5] Extra time-like dimensions have been a subject of interest for some time [18] and have been revived recently within the various versions of string and M-theory [19, 20] and the so-called Two-Time Physics [21, 22].

[6] It was shown also that most of theories with extra time have instantonic solutions [23] which may lead to the instability of flat space, but these solutions can be reinterpreted [20] so that the question of vacuum instability remains unclear.

however, phenomenological constraints on extra time-like dimensions have been revisited in the framework of brane world (with factorizable spacetime), where the only particle feeling the extra time(s) is the graviton [25]. It was argued there, that the induced imaginary part of the gravitational potential can be reinterpreted as an artifact of the fictitious decay into the unphysical negative energy tachyons and thus the size of extra time-like dimensions can be as large as $\tau_c \sim 1mm$! Since the graviton KK spectrum is quite different in the case with non-factorizable geometry considered here, we shall discuss now the phenomenology of the extra time in more details.

Let us first determine the mass spectrum of the graviton KK modes in the effective four-dimensional theory. The starting point is the five-dimensional Einstein equations

$$\sqrt{G}(R_{MN} - \frac{1}{2}G_{MN}R) =$$
$$-\frac{1}{M_*^3}[\Lambda\sqrt{G}G_{MN} + T_{vis}\sqrt{-g_{vis}}g^{vis}_{\mu\nu}\delta^\mu_M\delta^\nu_N\delta(\tau - \pi\tau_c) + T_{hid}\sqrt{-g_{hid}}g^{hid}_{\mu\nu}\delta^\mu_M\delta^\nu_N\delta(\tau)], \quad (8)$$

where G_{MN} $(M, N = \mu, \tau)$ is the five-dimensional metric and $g^{vis}_{\mu\nu} = G_{\mu\nu}(x^\mu, \tau = \pi)$ and $g^{hid}_{\mu\nu} = G_{\mu\nu}(x^\mu, \tau = 0)$ are four-dimensional metrics on the visible and hidden branes, respectively. It is easily verified that the actual solution to eq.(8) is given by (6) with condition (7) satisfied. Now let us look at the linear perturbations about this solution which can be parametrized by replacing $\eta_{\mu\nu}$ with $\eta_{\mu\nu} + h_{\mu\nu}(x, \tau)$. Upon compactification, the graviton field $h_{\mu\nu}(x, \tau)$ can be expanded into a KK tower as:

$$h_{\mu\nu}(x, \tau) = \sum_{n=0}^{\infty} h^{(n)}_{\mu\nu}(x)\psi^{(n)}(\tau), \quad (9)$$

where $h^{(n)}_{\mu\nu}(x)$ are KK modes of the graviton on the background of Minkowski space on the 3-brane. In the transverse traceless gauge $(\partial_\mu h^{\mu\nu} = h^\mu_\mu = 0)$ the equation of motion for $h^{(n)}_{\mu\nu}(x)$ is given by:

$$(\eta^{\mu\nu}\partial_\mu\partial_\nu + m_n^2)h^{(n)}_{\alpha\beta}(x) = 0. \quad (10)$$

Note that in contrast to the case of extra space-like dimension the sign of m_n^2 in (10) is flipped and thus this equation of motion describes graviton KK states with imaginary masses, i.e. tachyonic gravitons [25]. Imposing orthonormality condition for $\psi^{(n)}(\tau)$,

$$\int_{-\pi\tau_c}^{\pi\tau_c} d\tau e^{-2k|\tau|}\psi^{(m)}\psi^{(n)} = \delta_{mn}, \quad (11)$$

Einstein's equations (8) in conjunction with the above equation of motion (10) give the following differential equation for $\psi^{(n)}(\tau)$:

$$\frac{d}{d\tau}(e^{-4k|\tau|}\frac{d\psi^{(n)}}{d\tau}) = -m_n^2 e^{-2k|\tau|}\psi^{(n)}. \quad (12)$$

This is just the same equation as in the case of extra space-like dimension [11]. The solution to the eq.(12) is expressed by the Bessel functions of order two:

$$\psi^{(n)}(\tau) = \frac{e^{2k|\tau|}}{N_n}[J_2(z_n) + A_n Y_2(z_n)], \tag{13}$$

where $z_n(\tau) = \frac{m_n}{k}e^{k|\tau|}$, N_n is the normalization factor and A_n is a constant. The boundary conditions $\frac{d}{d\tau}\psi^{(n)}(\tau)|_{\tau=0,\pi} = 0$ lead to the following equations:

$$A_n = -\frac{J_1(z_n(0))}{Y_1(z_n(0))}, \tag{14}$$

$$A_n = -\frac{J_1(z_n(\pi))}{Y_1(z_n(\pi))}, \tag{15}$$

through which one can determine A_n and m_n. In fact, working in the limit $z_n(0) \ll 1$, one finds $A_n \sim z_n(0)^2 \approx 0$ and $J_1(z_n(\pi)) \approx 0$. Thus, the masses of the graviton KK modes given by $m_n = kz_n(\pi)e^{-k\tau_c\pi}$, are essentially determined through the roots of $J_1(z_n(\pi))$ and generally are not equally spaced, but in the limit $z_n(\pi) \gg 1$, $J_1(z_n(\pi))$ is approximated by $\sqrt{2/\pi z_n(\pi)}\cos(3\pi/4 - z_n(\pi))$ and thus,

$$\Delta m = m_{n+1} - m_n \approx \pi k e^{-k\tau_c\pi}. \tag{16}$$

Finally, from (11) one finds the normalization:

$$N_n \approx \frac{e^{\pi k\tau_c}}{\sqrt{k}}|J_2(z_n(\pi))| \xrightarrow[z_n(\pi)\to\infty]{} \frac{e^{\pi k\tau_c}}{\sqrt{k}}\sqrt{\frac{2}{\pi z_n(\pi)}}. \tag{17}$$

The zero mode wave function can be easily obtained from the general solution (13) by the limiting procedure $m_n \to 0$:

$$\psi^{(0)} = \sqrt{\frac{k}{1 - e^{-2\pi k\tau_c}}}. \tag{18}$$

Following Refs. [10, 15], we have also found a non-static (cosmological) solution and calculated the four-dimensional Hubble constant

$$H^2 = \frac{(T_{hid} + \varrho_{hid})^2}{36M_*^6} - \frac{\Lambda}{6M_*^3} = \frac{(T_{vis} + e^{-2\pi k\tau_c}\varrho_{vis})^2}{36M_*^6} - \frac{\Lambda}{6M_*^3}, \tag{19}$$

where ϱ_{hid} and ϱ_{vis} ($\varrho_{vis} = -e^{2\pi k\tau_c}\varrho_{hid}$) are matter energy densities on the hidden and visible branes, respectively. Taking into account (7) and $e^{-4k\pi\tau_c}\varrho_{hid}/M_*^4 \ll 1$, one obtains the desired form for the Hubble constant on the visible brane, $H^2 \approx T_{vis}e^{-2\pi k\tau_c}\varrho_{vis}/(18M_*^6)$, since now $T_{vis} > 0$.

Having determined the KK spectrum of the effective four-dimensional, theory we are ready now to discuss the possible influences of extra time on the ordinary

four-dimensional physics. The corrections appeared due to the graviton KK modes exchange to the gravitational potential of the two test point masses M_2 and M_1 placed at the points $(x = 0, \tau = \tau_c\pi)$ and $(|x| = r, \tau = \tau_c\pi)$ of the visible 3-brane, can be expressed as:

$$V(r) = \sum_{n=0}^{\infty} G_N^{(5)} \frac{M_1 M_2}{r} |\psi^{(n)}(z_n(\pi))|^2 e^{-im_n r} = G_N \frac{M_1 M_2}{r} + \delta V(r),$$
$$\delta V(r) = \sum_{n=1}^{\infty} G_N^{(5)} \frac{M_1 M_2}{r} |\psi^{(n)}(z_n(\pi))|^2 e^{-im_n r}, \tag{20}$$

where the five-dimensional Newton constant $G_N^{(5)} = 1/M_*^3$ is related to the ordinary four-dimensional one $G_N = 1/M_{Pl}^2$ as

$$G_N = G_N^{(5)} k (1 - e^{-2\pi k \tau_c})^{-1}. \tag{21}$$

Thus, an imaginary part is induced in the Newton's potential (20) as a result of tachyonic nature of the graviton KK modes [25]. Typically, such complex contributions to the energy are associated with an instability of the system. Let us consider, for example, two neutrons inside a nucleus. Taking the wave function to be [24]

$$\psi(r) = \frac{m_\pi^{3/2}}{\sqrt{\pi}} e^{-m_\pi r}, \tag{22}$$

(here m_π is the pion mass) we can calculate the gravitational energy of the system corresponding to (20):

$$E = \langle \psi | V(r) | \psi \rangle, \tag{23}$$

the imaginary part of which can be identified with a decay width of a neutron into "nothing" [24]:

$$\Gamma = \frac{16\zeta(3)}{\pi^3 k^3} m_N^2 m_\pi^4 G_N e^{5\pi k \tau_c}, \tag{24}$$

where m_N is the neutron mass, $\zeta(3) \approx 1.2$ is a Riemann's function value. In deriving (24) we use planar wave approximation to (13) with almost equidistantly distributed masses (16). Now taking, e.g. $k\tau_c \approx 12$ (and $k \approx M_{Pl}$), as it is desired for the solution of the hierarchy problem, we get the life-time for the disappearance of a neutron from a nucleus:

$$\tau_N \approx 10^{-7}\text{s}. \tag{25}$$

Needless to say, the value (25) is too low to be consistent with present observations. The experimental lower bound on the partial life-time of the decay $n \to \nu\nu\bar{\nu}$ is 40 orders of magnitude larger than (25). Thus, the extra time-like dimension even with a small size ($\tau_c \simeq O(10) M_{Pl}^{-1}$) which would be consistent with experiments in the case of factorizable geometry, sharply contradicts the current experimental observations on matter stability in the case of non-factorizable geometry considered here.

Let us note that the violation of probability in processes like the ones considered above just follows from the expected violation of causality in theories with extra time-like dimensions. However, violation of causality is not an indisputable consequence of the existence of extra time-like dimensions and deserves further study. Indeed, violation of causality can be viewed as a result of propagation of tachyonic KK modes of graviton with negative energies backward in ordinary time. Clearly, to get a consistent theory of tachyons, one could somehow remove the negative energy tachyonic states from the physical spectrum (for some earlier attempts, see [26]). We do not aim here to go into the details of tachyonic physics, but would like to simply note that it seems quite reasonable that any solution to the problem of negative energy tachyonic states would automatically solve the problem of violation of causality. In that case, the above-mentioned phenomenological inconsistencies can be disregarded.

To conclude, we consider some cosmological and phenomenological aspects of the Randall-Sundrum model with extra time-like dimension. We show that the introduction of the extra time-like dimension, instead of the extra space-like one previously proposed, helps to reconcile the solution to the hierarchy problem with the correct cosmological expansion of the visible universe. At the same time, we are faced with the problem of matter instability related to a possible violation of causality and probability which is typical for the theories with extra time-like dimensions, although, as stressed above, a clear-cut conclusion is by far less obvious and the problem deserves further study [27].

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